Marine Pollution Bulletin 146 (2019) 106–116

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Baseline

Spatial variation of trace element concentration and contamination assessment in the coral reef sediments of Lakshadweep Archipelago, Indian Ocean

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ARTICLE INFO

Keywords:
Coral reef sediments
Trace elements
Geochemical indices
Potential ecological risk index

ABSTRACT

Surface sediments were collected from the shore and lagoons of Kavaratti, Kadmat and Agatti islands of Lakshadweep Archipelago and analysed for trace element concentration. The sediment contamination was assessed on the basis of geochemical, biological hazard and ecological risk indices. Except Cd and Pb, all the other trace elements selected for the study were below the contamination level. Compared to Kadmat, Kavaratti and Agatti were more polluted and the pollution was pronounced in lagoons than shore. Population pressure, untreated sewage, diesel based power generation, shipping and tourism activities contribute to sediment contamination. Statistical analysis revealed the association of trace elements with sedimentary characteristics due to anthropogenic sources.

Trace elements are the most toxic, abundant and persistent pollutants that can accumulate in marine habitats and increases the concentration through biomagnification (Chakraborty et al., 2010). These are transported to the marine environment through natural and anthropogenic processes as dissolved species in water or in association with suspended sediments. Trace elements have the potential to affect sediment nutrient cycling, cell growth and regeneration as well as reproductive cycles and photosynthetic potential of marine organisms (Bricker, 1993). The geochemical investigation of sediment provides information about trace elements in the aquatic systems (Boamponsem et al., 2010).

Lakshadweep is an archipelago of coral islands scattered in the Arabian Sea off the West Coast of India. It consists of 36 tiny islands, 12 atolls, 3 reefs and 5 submerged banks, covering an area of 32 km^2 with lagoons occupying about 4200 km^2. Lakshadweep has a total population of 64,429 with a population density of 2013 persons/km^2, which is one of the highest in India (LAPCC, 2012). The islands are flat and scarcely rise more than two meters and are vulnerable to storms and sea erosion. They are made up of coral sand and boulders which have been compacted into sandstone. The lagoons have sandy bottoms with scattered coral boulders and pinnacles followed by extensive sea grass beds at the landward side (James et al., 1986). According to Pillai (1986) 105 species of corals under 37 genera were recorded from Lakshadweep.

The livelihood of the islanders of Lakshadweep Archipelago is greatly dependent on coral reefs, as they provide food, income, employment, shelter and protection. The geochemical aspect of trace elements within the reef environment requires an attention as it can assess the pollution status of the ecosystem. Hence a baseline data regarding the trace element pollution is essential to assess the health of these coastal ecosystems. The present study is an attempt to assess the contamination and spatial distribution pattern of seven trace elements (Cr, Mn, Fe, Cu, Zn, Cd and Pb) in the shore and lagoon sediments of three inhabited islands, namely, Kavaratti, Kadmat and Agatti belonging to Lakshadweep Archipelago.

Kavaratti is the capital of Lakshadweep Archipelago. It is a popular tourist destination due to the presence of pristine white sand beaches and calm lagoons. Kavaratti having an area of 3.93 km^2 lies 360 km away from the Kerala coast at 10° 32′ and 10° 35′ N latitude and 72° 35′ and 72° 40′ E longitude. The maximum length and width of the island is 5.8 and 1.6 km respectively. It is the most populated island in Lakshadweep. It has a lagoon area of 8.96 km^2. This island ranked first among the islands with 86 species of corals and live coral coverage was recorded as 39% (Pillai and Jasmine, 1989). Kadmat is located at 11° 10′ and 11° 16′ N latitude and 72° 45′ and 72° 48′ E longitude, with an area of 3.20 km^2. The lagoon has a width of 1.5 km. It is the central

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https://doi.org/10.1016/j.marpolbul.2019.06.003
Received 6 March 2019; Received in revised form 22 May 2019; Accepted 1 June 2019

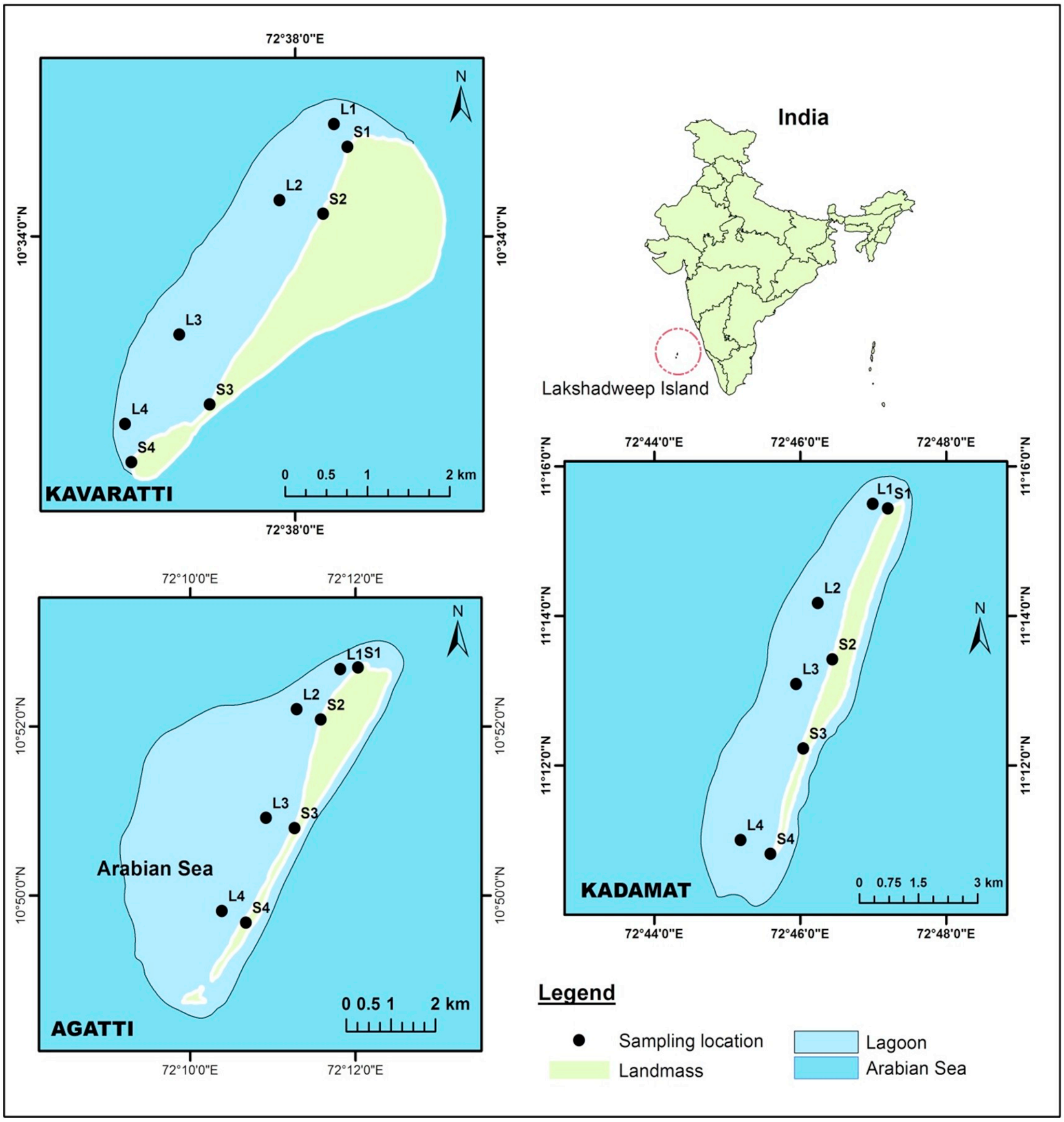

Fig. 1. Location map.

most island of the Lakshadweep Archipelago. Agatti, having an area of 3.84 km^2 and a maximum length of 10 km lies at 10° 48′ and 10° 53′ N latitude and 72° 09′ and 72° 13′ E longitude. The lagoon area of this island is 17.50 km^2. Agatti houses the only airport and airstrip in Lakshadweep Archipelago (Fig. 1).

The sampling locations and their geographical co-ordinates are given in Table 1. Sediment samples were collected from the shore and lagoon stations of Kavaratti, Kadmat and Agatti Islands in Lakshadweep Archipelago during May 2015. Twenty four stations were selected for the study. The lagoon stations point towards ocean from the shore and distance between the stations was 100 m. From each location on the shore, surface sediment samples were collected from 3 to 5 cm depth using a clean plastic spoon and were stored in polythene bags. Sediments from lagoon (3 m depth) were collected by scuba diving. Subsamples were also taken from each station and the reproducibility of sampling was checked by triplicate sub sampling measurements. These were kept in icebox storage for transportation to the laboratory and stored in deep freezers (−20 °C) till all the analyses were performed. In the laboratory the sediment samples were freeze-dried, homogenized and ground to a fine powder for sieving (74 μm) using an agate mortar and pestle prior to analysis.

Sedimentary pH was measured using calibrated pH meter after shaking the suspension of air dried sediment and water for half an hour. The sediment texture or grain size was determined by dry sieve analysis using a standard set of ASTM sieves in a Ro-Tap sieve shaker. The standard classification for particles into Wentworth size classes was accepted to classify the textural characteristics of sandy sediments as coarse sand, medium sand and fine sand (Folk, 1974). The total organic carbon (TOC) was determined volumetrically by wet oxidation method as outlined by Walkley and Black (1934). The calcium carbonate content was determined according to Dreimanis (1962). For the determination of the total trace metals, 1 g of the powdered homogenized sediment was digested in Teflon vessels with a mixture of concentrated HNO_3 and $HClO_4$ acids (5:1) at 120 °C for 2 h, following the procedure of Loring and Rantala, 1992. The concentrations of trace elements (Cr, Mn, Fe, Cu, Zn, Cd and Pb) were estimated using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES, Perkin Elmer Optima 8000). Replicate samples, calibration standards, and method blanks were used to monitor the performance of the instrument and the quality of the data. All reagents used in the analysis were analytical reagent select grade (Merck). Reagent blank was processed with the samples and did not show any significant contamination. The precision of the

Table 1
Sampling locations and geographical co-ordinates [S – shore, L – lagoon].

	Station	Land mark	Latitude	Longitude
Kavaratti (KV)	S1	Jetty	10.5673	72.6358
	S2	School	10.5414	72.6184
	S3	Chicken neck	10.5413	72.6184
	S4	Helipad	10.5401	72.6186
	L1	Entrance	10.5786	72.6376
	L2	Guest house	10.5695	72.6303
	L3	Harbour office	10.5561	72.6206
	L4	Helipad	11.2255	72.7748
Kadmat (KD)	S1	Light house	11.2241	72.7752
	S2	Deck bungalow	11.5714	72.6371
	S3	Family hut	11.2037	72.7673
	S4	Helipad	11.1803	72.7599
	L1	Light house	11.2582	72.7832
	L2	Civil station	11.2362	72.7707
	L3	Football ground	11.2181	72.7657
	L4	Helipad	11.1846	72.7533
Agatti (AG)	S1	Jetty	10.8670	72.1928
	S2	Coir factory	10.8562	72.1905
	S3	CMLRE	10.8466	72.1877
	S4	Airport	10.8280	72.1779
	L1	Jetty	10.8794	72.2012
	L2	Coir factory	10.8720	72.1880
	L3	CMLRE	10.8506	72.1870
	L4	Airport	10.8302	72.1730

Table 2
Comparison of MESS 2 certified and obtained values for total trace elements.

Metals	Cr	Mn	Fe	Cu	Zn	Cd	Pb
Certified value	105	324	4.34	33.9	159	0.24	21.1
Obtained value	108.04	312.98	4.10	34.37	154.79	0.23	20.97
Recovery %	102.9	96.6	94.6	101.4	97.35	98.3	99.4

analytical procedure was checked by analysing standard reference materials of commercially available standards (TraceCERT Sigma-Aldrich Optima Family Multi-Element standard solution in nitric acid in triplicates). The concentrations of the selected elements in the standards were accurate up to ± 0.5% of certified value. All analyses were taken in triplicates and mean values were calculated. The detection limits of ICP -OES for the elements were 0.01 mg/kg for Fe and 0.001 mg/kg for Cd, Cr, Cu, Mn, Zn and Pb. Moreover, to evaluate the accuracy of metal analysis MESS 2 certified reference material was exposed to the same procedure. Triplicate analysis of reference samples showed a good accuracy and the recovery rate ranged between 94.6% and 102.9% (Table 2).

The spatial distribution of pH, TOC, $CaCO_3$ and trace elements (Cr, Mn, Fe, Cu, Zn, Cd and Pb) were shown in Figs. 2 and 3 respectively. In the present study, the predominant grain size constituent of sediments from the sampling sites was 100% sand. Medium sand was the dominant fraction than coarse and fine sand.

The average concentration of trace elements in the study area on spatial basis followed the order: Fe > Pb > Cd > Mn > Cr > Zn > Cu in shore and lagoon stations of Kavaratti, Fe > Pb > Cd > Cu > Mn > Cr > Zn in shore stations of Kadmat, Pb > Fe > Cd > Mn > Cr > Cu > Zn in lagoon stations of Kadmat and Pb > Fe > Cd > Mn > Cr > Cu > Zn in shore and lagoon stations of Agatti. The concentration of Pb was found to be maximum in the Airport station (S4) of Agatti. In Kadmat, Cd and Pb had their maximum values at the Helipad station (S4). In Kavaratti, the maximum concentrations of most of the elements were found to be maximum in stations near to Helipad (S4) and Jetty (S1). Powerhouse, boat building yards and fish processing centres were functioning in Jetty station. The trace element concentrations were found to be higher than that of the background concentration only in the case of Cd and

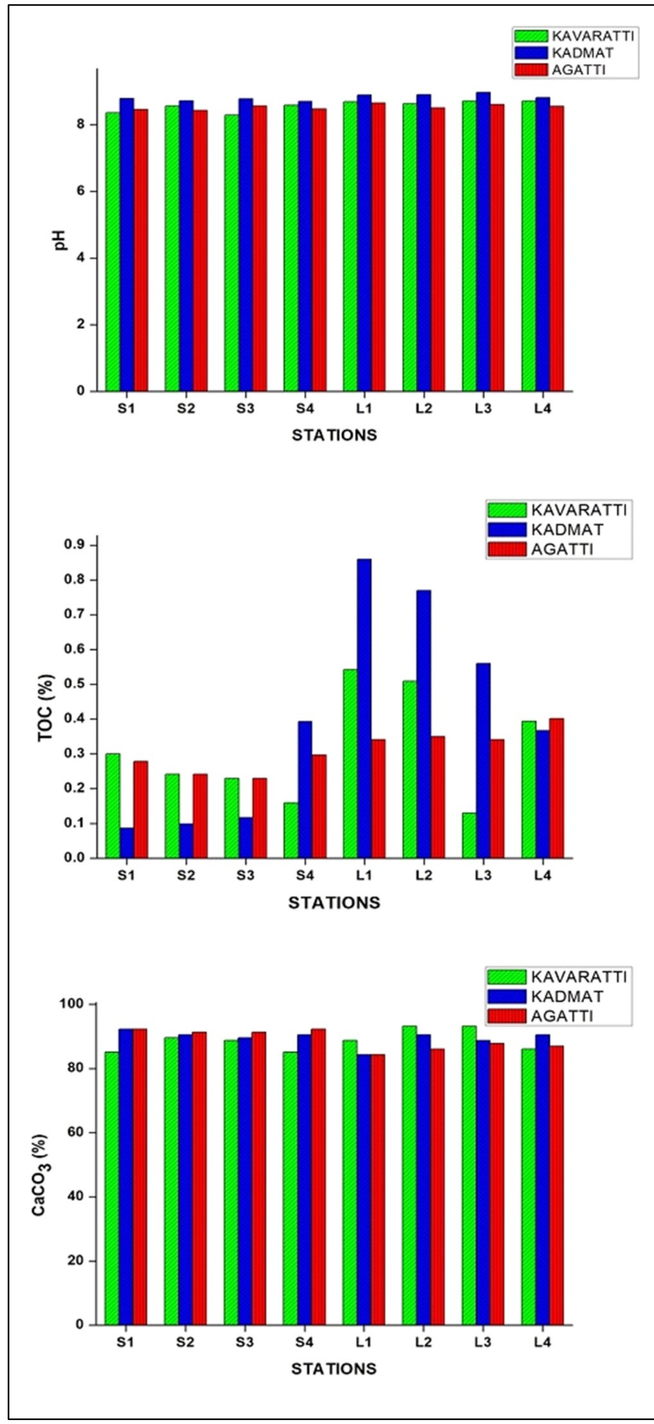

Fig. 2. Spatial variation of pH, TOC and $CaCO_3$.

Pb, with their maximum values in Agatti and Kavaratti and minimum in Kadmat. A comparison of trace element concentrations between the present study and of different coral reef sediments around the world and India is shown in Table 3.

The sediment contamination was assessed based on geochemical, biological hazard and ecological risk indices. The different geochemical indices used in this study are contamination factor (C_F), geoaccumulation index (Igeo), contamination degree (C_d), modified degree of contamination (mC_d), and sediment pollution index (SPI) (Table 4).

The level of contamination of sediment by a metal is often expressed in terms of contamination factor (C_F) and is calculated as:

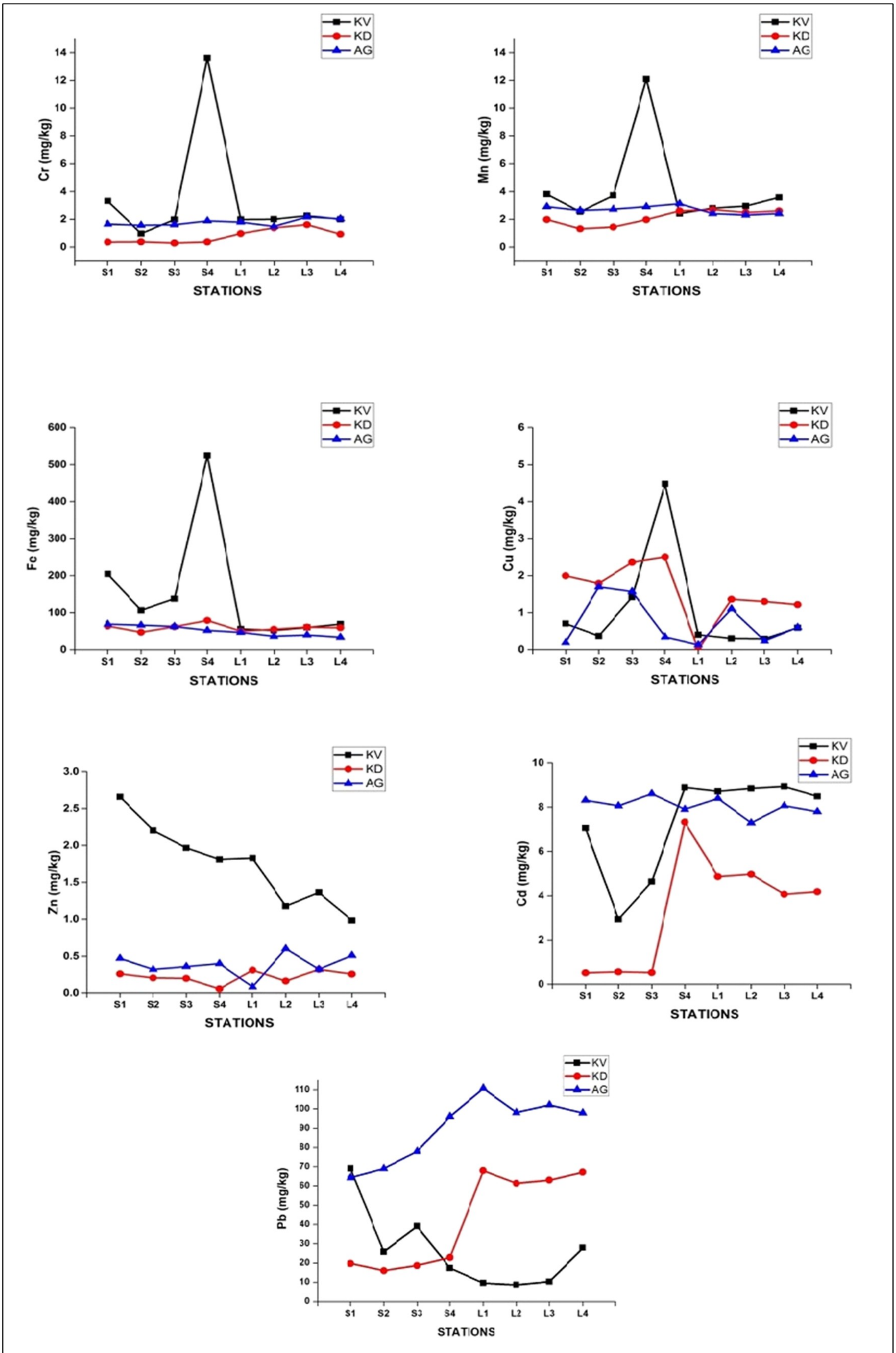

Fig. 3. Spatial variation of trace element concentrations (Cr, Mn, Fe, Cu, Zn, Cd, Pb).

Table 3
Comparison of trace element concentrations (mg/kg) between present study and different coral reef sediments around the world and India.

Location	Fe	Mn	Cu	Cd	Cr	Pb	Zn	Reference
Kavaratti Island, Lakshadweep	151.19	4.24	1.07	7.32	3.51	25.94	1.75	Present Study
Agatti Island, Lakshadweep	50.64	2.67	0.73	8.05	1.77	89.53	0.38	Present Study
Kadmat Island, Lakshadweep	59.63	2.14	1.57	3.38	0.78	42.13	0.22	Present Study
Koswari Island, Gulf of Mannar	30,987.9	147	54.2	–	67.5	496.7	16.9	Krishnakumar et al., 2017
Van Island, Gulf of Mannar	31,218.9	162.5	57.81	–	108.73	348.4	52.5	Krishnakumar et al., 2016
Northern Red Sea, Egypt	321.5–2150.60		1.09–11.25	1.97–4.30		3.67–12.64	3.09–27.80	Ali et al., 2011
Andaman Islands, India	2008.3–2636	38.9–52.68	5.5–10.6	–	8.9–22.1	–	25.5–38.8	Nobi et al., 2010
Gulf of Mannar, India	12,600	305	57	0.16	177	16	73	Jonathan et al., 2004
Kavaratti Island, Lakshadweep	63.73	9.94	5.05	5.48	10.08	32.42	36.17	Anu, 2002
Agatti Island, Lakshadweep	37.12	2.28	3.74	25.66	9.54	4.53	25.53	Anu, 2002
Kiltan Island, Lakshadweep	23.31	5.95	3.31	6.99	9.84	30.74	28.26	Anu, 2002
Minicoy Island, Lakshadweep	25.88	8.47	3.9	8.24	8.55	28.83	5.06	Anu, 2002
Kavaratti Island, Lakshadweep	66	43.2	1.2	–	2.6	–	3.3	Anandaraj, 2002
Minicoy Island, Lakshadweep	26–668	8.8–35.8	0.4–6.8		10.2–31.4	–	0.6–38.6	Anandaraj, 2002
Gulf of Mannar, India	1152–4235	46.2–125.6	7.5–18.4	–	–	–	15.2–28.5	Kumaresan et al., 1998

Table 4
Range and classification of geochemical indices.

Parameters	Range of values	Contamination category	References
Contamination factor (C_F)	$C_F < 1$	Low contamination	Håkanson, 1980
	$1 \geq C_F > 3$	Moderate contamination	
	$3 \geq C_F \geq 6$	Considerable contamination	
	$C_F > 6$	Very high contamination	
Contamination degree (C_d)	$C_d < n$	Low	Håkanson, 1980
	$n \leq C_d < 2n$	Moderate	
	$2n \leq C_d < 4n$	Considerable	
	$C_d \geq 4n$	Very high	
Modified degree of contamination (mC_d)	$mC_d < 1.5$	Nil to low	Abrahim and Parker, 2008
	$mC_d < 2$	Low	
	$mC_d < 4$	Moderate	
	$mC_d < 8$	High	
	$mC_d < 16$	Very high	
	$mC_d < 32$	Extremely high	
	$mC_d > 32$	Ultra high	
Geoaccumulation index (Igeo)	Igeo ≤ 0	Unpolluted	Müller, 1969
	Igeo = 0–1	Unpolluted to moderately polluted	
	Igeo = 1–2	Moderately polluted	
	Igeo = 2–3	Moderately to strongly polluted	
	Igeo = 3–4	Strongly polluted	
	Igeo = 4–5	Strongly to extremely polluted	
	Igeo > 5	Extremely polluted	
Sediment pollution index (SPI)	0–2	Natural	Singh et al., 2002
	2–5	Low polluted	
	5–10	Moderately polluted	
	10–20	Highly polluted	
	> 20	Dangerous	

$$C_F = \frac{M_s}{M_b}$$

where Ms and Mb represent metal concentration in the sediment analysed and background concentration of the respective metal. The metal background values were from the crustal abundance reported by Taylor (1964). According to Hakanson's classification, except for Cd and Pb, all other trace elements in the study area had $C_F < 1$ and hence belong to low pollution category (Table 8). This suggests that these metals originated to a large extent from the earth's crust via weathering. On the other hand, Cd and Pb were originated from both natural and anthropogenic sources and may exhibit extreme toxicity even at trace levels.

On the basis of C_F values for Cd, the shore samples of Kavaratti and Agatti and lagoon samples of the three islands belonged to very high contamination category. The lagoons of Kadmat and Agatti belong to considerable to very high contamination level respectively for Pb (Fig. 4).

Geoaccumulation index (Igeo) is a simple measure to assess the temporal variation of trace elements by comparing the present-day metal concentrations in aquatic sediments with the geochemical background and has been widely applied for evaluating individual metal pollution, employing the equation (Müller, 1969).

$$Igeo = \log_2\left[\frac{C_n}{1.5B_n}\right]$$

where C_n is the concentration of metal analysed, B_n is the background level of the metal and 1.5 is the background matrix correction factor due to lithogenic effects. None of the stations showed signs of sediment contamination for the trace elements - Cr, Mn, Fe, Cu and Zn as Igeo was negative for these elements. But Cd and Pb have significant values for Igeo which suggest its pollution mainly due to anthropogenic activities (Table 8). The percentagewise distribution of samples in each contamination category for Cd and Pb are shown in Fig. 4.

Contamination degree (C_d) is mathematically expressed as:

$$C_d = \sum_{i=1}^{i=n} C_F^i$$

where $C_F{}^i$ the contamination factor for the ith element and n is the number of metals. Contamination degree of all sites indicated that lagoons were more polluted than shore stations in the whole study area (Table 9). Agatti was the most polluted and Kadmat was the least in the case of both shore and lagoons. The shore and lagoons of Agatti were under very high contamination category. The lagoons and 50% shore samples of Kavaratti fall under the same class. Very high contamination was observed in 50% lagoons and 25% shore samples of Kadmat (Fig. 4).

The modified degree of contamination (mC_d) is mathematically expressed as:

$$mC_d = \frac{\sum_{i=1}^{i=n} C_F^i}{n}$$

where $C_F{}^i$ is the contamination factor for the i-th element and n is the number of metals (Table 9). The shore and lagoons of Agatti fall under high contamination category. In Kavaratti, 50% shore and all lagoon stations showed high contamination. High contamination was observed in the 50% lagoon and 25% shore samples of Kadmat whereas, 75% shore samples were under low pollution category (Fig. 4).

Sediment pollution index (SPI) is defined as the linear sum of the metal enrichment factors along with the account of metal toxicity

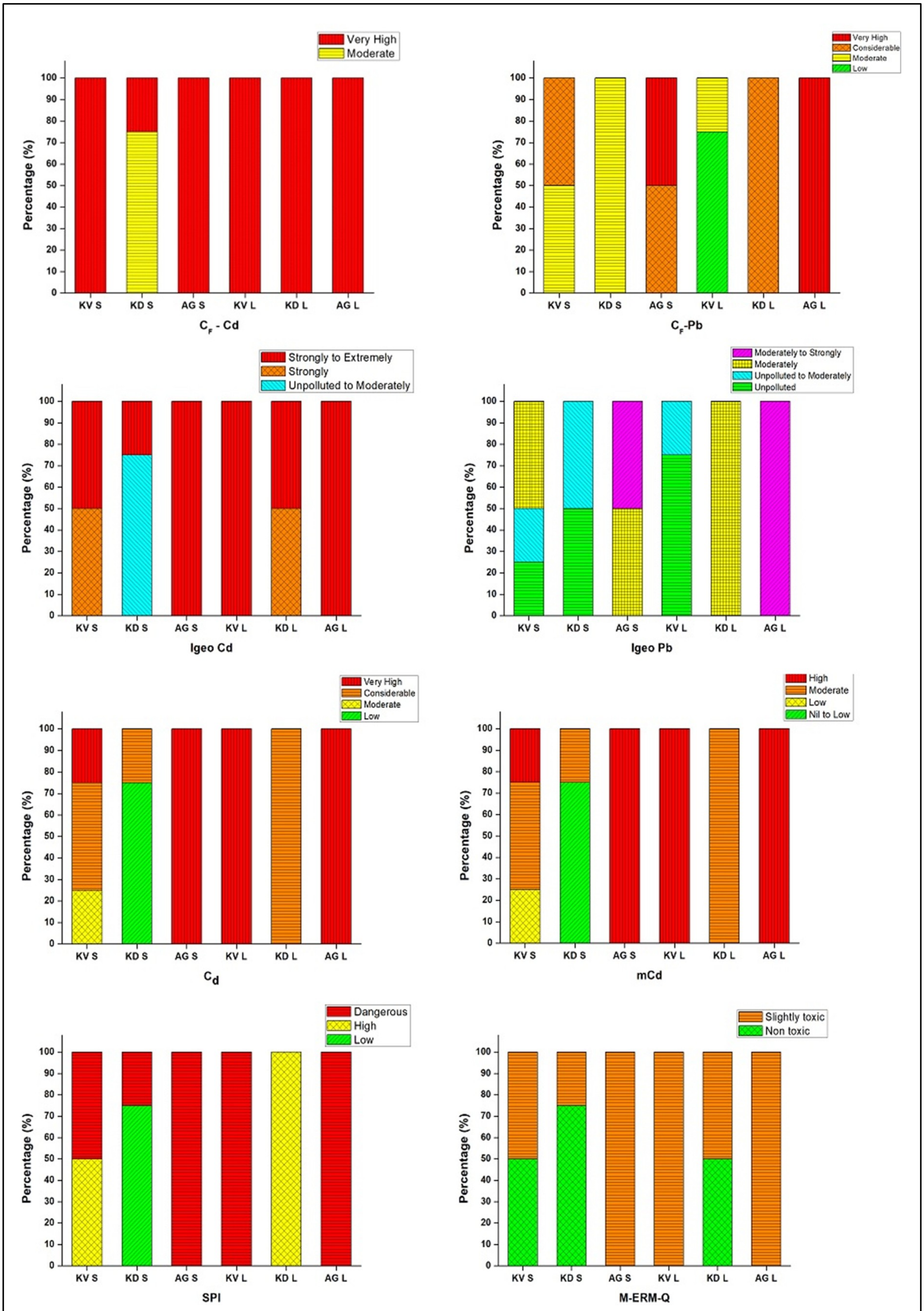

Fig. 4. Percentage of samples in the corresponding contamination category based on geochemical indices.

Table 5
Sediment Quality Guidelines (Long et al., 1995).

Metal	TEL	PEL	ERL	ERM
Cr	52.3	160	81	370
Mn	–	–	460	1100
Fe	–	–	20,000	40,000
Cu	18.7	108	34	270
Zn	124	271	150	410
Cd	0.68	4.21	1.2	9.6
Pb	30.2	112	46.7	220

weights and is adopted to assess the sediment quality (Singh et al., 2002). SPI can be expressed as:

$$SPI = \frac{\sum (C_F^i X W_i)}{\sum W_i}$$

where W_i is the toxicity weight of metal i. Toxicity weight, 1 was assigned for Cr, Zn and Mn; 2 was assigned for Cu; 5 for Pb and 30 for Cd. In Kavaratti, 50% shore and all lagoon samples were under dangerous contamination and the remaining 50% shore samples belonged to high contamination. Based on SPI values, (Table 9) the island Agatti was under dangerous pollution without any difference between shore and lagoon (Fig. 4).

The biological hazards to the aquatic environment were assessed based on Sediment Quality Guidelines (SQGs) (Table 5). Effects range-low (ERL) and effects range-median (ERM), threshold effect level (TEL) and probable effects level (PEL), mean ERM quotient (M-ERM-Q) and hazard quotient (HQ) are the biological hazard assessment indices used in the present study (Table 6).

The chemical concentrations corresponding to the lower or 10th and 50th or median percentiles of adverse biological effects were called the effects-range-low (ERL) and effects range-median (ERM) guidelines, respectively (Long et al., 1995). Except for Cd and Pb, all other trace elements in the study area had their concentrations below ERL and hence associated with minimal effects. In the case of Cd, both the shore and lagoon sediments of Kavaratti and Agatti had their concentrations between ERL and ERM and adverse effects were expected to occur occasionally. The concentrations of Pb were between ERL and ERM and occasional adverse effects were expected to occur in both shore and lagoons of Agatti and lagoons of Kadmat.

Another sediment quality guideline which is most widely used to assess the ecotoxicology of sediments is the threshold effect level (TEL) and the probable effects level (PEL) approach (Long et al., 1998). Except for Cd and Pb, all other trace elements in the study area have their concentrations below TEL and hence rarely associated with adverse biological effects. For Cd, both the shore and lagoon sediments of Agatti and lagoon sediments of Kavaratti had their concentrations above PEL and adverse effects were expected to occur frequently. The shore and lagoons of Agatti and lagoons of Kadmat had their Pb concentrations between TEL and PEL and occasional adverse effects were expected.

The mean ERM quotient (M-ERM-Q) method has been applied to determine the possible biological effect of combined toxicant groups by calculating the mean quotients for a large range of contaminants using the following formula (Long, 2006):

$$M - ERM - Q = \sum_{i=1}^{n} (C_i/ERM_i)/n$$

where C_i is the concentration of metal i, ERM_i is the ERM values for metal i and n is the number of metal i. In the present study, based on M-ERM-Q values (Table 9), 75% shore stations of Kadmat and 50% shore stations of Kavaratti were non-toxic and all the other stations of the three islands belonged to slightly toxic condition with 21% probability of toxicity (Fig. 4).

The potential toxic risk to aquatic ecosystem can also be evaluated by calculating the hazard quotients (HQ) of the chemical contaminants using the equation (Urban and Cook, 1986):

$$HQ = \frac{SCC}{SQG}$$

where SCC is the sediment chemical concentration in mg/kg, and SQG is the sediment quality guideline in mg/kg. SQG values were determined at ERL levels according to Long et al., 1995. In the present study, HQ values were < 0.1 for the trace elements – Cr, Mn, Fe, Cu and Zn and hence no adverse effects. The shore and lagoons of Kavaratti and Agatti and lagoons of Kadmat were associated with moderate potential hazards of Cd. In the case of Pb, moderate potential hazards were expected to occur in Agatti, lagoons of Kadmat and 25% shore samples of Kavaratti (Table 8).

The ecological risk assessment indices used in the present study are potential ecological risk coefficient (E_r^i) and potential ecological risk index (RI) (Table 7). The potential ecological risk coefficient (E_r^i) of a single element and the potential ecological risk index (*RI*) of the multi element can be calculated via the following equations:

$$E_r^i = T_r^i \times C_F^i$$

$$C_f^i = C_s^i / C_b^i$$

$$RI = \sum_{i=1}^{n} E_r^i$$

where $T_r{}^i$ is the toxic response factor for the given element of "i", which accounts for the toxic requirement and the sensitivity requirement. $C_F{}^i$ is the contamination factor of a single element of "i"; $C_s{}^i$ is the measured concentration of sedimentary trace element, $C_b{}^i$ is the background concentration of sedimentary trace element.

All other trace elements except Cd had low ecological risk in the

Table 6
Range and classification of biological hazard assessment indices.

Index	Classification	Description	References
ERL and ERM	< ERL	Minimal effects range	Long et al., 1995
	Between ERL and ERM	Effects would occasionally occur	
	> ERM	Effects would frequently occur	
M-ERM-Q	< 0.1	9% probability of toxicity (non-toxic)	Wang et al., 2015
	0.11–0.5	21% probability of toxicity (slightly toxic)	
	0.51–1.5	49% probability of toxicity (medium toxic)	
	> 1.51	76% probability of toxicity (highly toxic)	
TEL and PEL	≤ TEL	Rarely associated with adverse biological effects	Long et al., 1998
	Between TEL and PEL	Occasionally associated with adverse biological effects	
	≥ PEL	Frequently associated with adverse biological effects	
HQ	< 0.1	No adverse effects	Urban and Cook, 1986
	0.1–1	Low potential hazards	
	1–10	Moderate hazards	
	> 10	High hazards	

Table 7
Range and classification of ecological risk assessment indices (Håkanson, 1980).

E_r^i value	Grades of ecological risk of single metal (ecological risk factor)
$E_r^i < 40$	Low
$40 \le E_r^i < 80$	Moderate
$80 \le E_r^i < 160$	Considerable
$160 \le E_r^i < 320$	High
$E_r^i \ge 320$	Serious

RI value	Grades of potential ecological risk of the environment (ecological risk index)
RI < 150	Low
150 ≤ RI < 300	Moderate
300 ≤ RI < 600	High
RI ≥ 600	Significantly high

Table 8
Mean concentrations of C_F, Igeo, HQ and E_r^i in sediments.

Island	Station	Cr	Mn	Fe	Cu	Zn	Cd	Pb
C_F								
KV	S	0.050 ± 0.06	0.006 ± 0.00	0.004 ± 0.00	0.032 ± 0.034	0.031 ± 0.00	29.42 ± 13.12	3.03 ± 1.81
	L	0.021 ± 0.00	0.003 ± 0.00	0.001 ± 0.00	0.007 ± 0.003	0.019 ± 0.00	43.75 ± 0.97	1.12 ± 0.74
KD	S	0.004 ± 0.00	0.002 ± 0.00	0.001 ± 0.00	0.0395 ± 0.01	0.003 ± 0.00	11.19 ± 16.97	1.55 ± 0.23
	L	0.012 ± 0.00	0.003 ± 0.00	0.001 ± 0.00	0.024 ± 0.001	0.004 ± 0.00	22.62 ± 2.31	5.19 ± 0.26
AG	S	0.017 ± 0.00	0.003 ± 0.00	0.001 ± 0.00	0.018 ± 0.014	0.006 ± 0.00	41.11 ± 1.56	6.15 ± 1.12
	L	0.019 ± 0.00	0.003 ± 0.00	0.001 ± 0.00	0.009 ± 0.008	0.005 ± 0.00	39.44 ± 2.35	8.18 ± 0.48
Igeo								
KV	S	−5.62 ± 1.62	−8.28 ± 0.97	−8.73 ± 1.01	−6.18 ± 1.54	−5.62 ± 0.24	4.17 ± 0.70	0.82 ± 0.85
	L	−6.19 ± 0.09	−8.94 ± 0.23	−10.49 ± 0.18	−7.76 ± 0.47	−6.33 ± 0.38	4.86 ± 0.03	−0.60 ± 0.79
KD	S	−8.75 ± 0.17	−9.76 ± 0.31	−10.41 ± 0.31	−5.27 ± 0.22	−9.38 ± 0.99	1.79 ± 1.88	0.035 ± 0.21
	L	−6.98 ± 0.39	−9.10 ± 0.05	−10.55 ± 0.13	−6.00 ± 0.08	−8.69 ± 0.45	3.91 ± 0.15	1.79 ± 0.07
AG	S	−6.49 ± 0.12	−9.00 ± 0.07	−10.41 ± 0.18	−6.99 ± 1.58	−8.10 ± 0.24	4.78 ± 0.05	2.02 ± 0.25
	L	−6.34 ± 0.24	−9.13 ± 0.20	−11.10 ± 0.20	−7.77 ± 1.37	−8.45 ± 1.30	4.71 ± 0.09	2.44 ± 0.08
HQ								
KV	S	0.061 ± 0.07	0.012 ± 0.01	0.012 ± 0.01	0.051 ± 0.05	0.014 ± 0.00	4.90 ± 2.19	0.81 ± 0.48
	L	0.026 ± 0.00	0.006 ± 0.00	0.003 ± 0.00	0.012 ± 0.00	0.009 ± 0.00	7.29 ± 0.16	0.301 ± 0.20
KD	S	0.004 ± 0.00	0.003 ± 0.00	0.003 ± 0.00	0.064 ± 0.01	0.001 ± 0.00	1.86 ± 2.83	0.414 ± 0.06
	L	0.015 ± 0.00	0.006 ± 0.00	0.003 ± 0.00	0.038 ± 0.00	0.002 ± 0.00	3.77 ± 0.38	1.39 ± 0.07
AG	S	0.020 ± 0.00	0.006 ± 0.00	0.003 ± 0.00	0.028 ± 0.02	0.002 ± 0.00	6.85 ± 0.26	1.64 ± 0.30
	L	0.023 ± 0.00	0.005 ± 0.00	0.002 ± 0.00	0.015 ± 0.01	0.002 ± 0.00	6.57 ± 0.39	2.19 ± 0.13
E_r^i								
KV	S	0.100 ± 0.11	0.006 ± 0.00	–	0.158 ± 0.17	0.031 ± 0.00	882.62 ± 393.64	15.13 ± 0.9.06
	L	0.042 ± 0.00	0.003 ± 0.00	–	0.034 ± 0.10	0.019 ± 0.00	1312.63 ± 28.99	5.62 ± 3.70
KD	S	0.01 ± 0.00	0.002 ± 0.00	–	0.195 ± 0.03	0.003 ± 0.00	335.84 ± 509.08	7.74 ± 1.13
	L	0.025 ± 0.00	0.003 ± 0.00	–	0.087 ± 0.06	0.004 ± 0.00	678.60 ± 69.30	25.97 ± 1.28
AG	S	0.032 ± 0.00	0.003 ± 0.00	–	0.085 ± 0.07	0.006 ± 0.00	1233.45 ± 46.82	30.74 ± 5.60
	L	0.037 ± 0.00	0.003 ± 0.00	–	0.045 ± 0.04	0.005 ± 0.00	1183.29 ± 70.44	40.89 ± 2.41

KV – Kavaratti, KD – Kadmat, AG – Agatti, S – shore, L – lagoon.

Table 9
Mean concentrations of C_d, mC_d, SPI, M-ERM-Q and RI in sediments.

Island	Station	C_d	mC_d	SPI	M-ERM-Q	RI
Kavaratti	S	32.57 ± 13.41	4.65 ± 1.92	22.45 ± 9.85	0.118 ± 0.04	898.04 ± 394.42
	L	44.93 ± 0.48	6.42 ± 0.07	32.95 ± 0.641	0.141 ± 0.00	1318.35 ± 25.81
Kadmat	S	12.79 ± 17.16	1.82 ± 2.45	8.59 ± 12.75	0.048 ± 0.05	343.79 ± 510.03
	L	27.85 ± 2.29	3.98 ± 0.33	17.61 ± 1.73	0.111 ± 0.01	704.69 ± 69.16
Agatti	S	47.30 ± 1.49	6.76 ± 0.21	31.60 ± 1.12	0.174 ± 0.01	1264.32 ± 44.73
	L	47.66 ± 2.76	6.81 ± 0.39	30.60 ± 1.81	0.185 ± 0.01	1224.27 ± 72.47

entire study area (Table 8). Both the shore and lagoon samples of Kavaratti and Agatti were facing serious ecological risk. Potential ecological risk index, RI > 600 in all shore and lagoon stations of Kavaratti and Agatti and were categorized as significantly high potential ecological risk. The lagoons of Kadmat and 25% shore samples were also having the same level of risk whereas 75% shore samples had only low levels of potential ecological risk (Table 9).

Pearson's correlation analysis performed between trace element concentrations and general sedimentary parameters in shore and lagoon stations is depicted in Table 10. In shore sediments, significant negative correlations were noticed between pH and the trace elements - Zn, Cd and Pb ($p < 0.05$). Similarly in lagoon sediments, significant negative correlation ($p < 0.01$) was noticed between pH and Cd. Low pH will affect the speciation and bioavailability of many trace elements and generally increases the proportion of free dissolved forms of toxic elements (Millero, 2009). TOC showed significant positive correlation

Table 10
Pearson correlations for metal concentrations in shore and lagoon sediments.

	pH	TOC	Coarse	Medium	Fine	$CaCO_3$	Cr	Mn	Fe	Cu	Zn	Cd	Pb
Shore													
pH	1												
TOC	−0.506	1											
Coarse	−0.350	0.391	1										
Medium	0.597*	−0.230	−0.635*	1									
Fine	−0.354	−0.143	−0.307	−0.540	1								
$CaCO_3$	0.268	0.001	0.427	−0.086	−0.360	1							
Cr	−0.166	−0.099	−0.082	0.057	0.019	−0.682*	1						
Mn	−0.203	−0.070	−0.065	0.004	0.067	−0.670*	0.994**	1					
Fe	−0.154	−0.093	−0.200	0.080	0.119	−0.805**	0.972**	0.973**	1				
Cu	0.433	−0.370	−0.586*	0.460	0.072	−0.415	0.627*	0.614*	0.643*	1			
Zn	−0.578*	0.143	−0.082	−0.266	0.418	−0.782**	0.441	0.470	0.569	−0.100	1		
Cd	−0.580*	0.687*	0.423	−0.178	−0.242	−0.140	0.453	0.463	0.348	−0.004	0.127	1	
Pb	−0.628*	0.507	0.498	−0.277	−0.201	0.253	−0.117	−0.125	−0.252	−0.587*	−0.022	0.647*	1
Lagoon													
pH	1												
TOC	0.596*	1											
Coarse	−0.093	−0.358	1										
Medium	−0.310	−0.157	−0.066	1									
Fine	0.241	0.400	−0.862**	−0.448	1								
$CaCO_3$	0.112	−0.212	−0.372	−0.200	0.435	1							
Cr	−0.551	−0.564	−0.207	−0.009	0.190	0.238	1						
Mn	0.064	−0.199	0.584*	−0.162	−0.441	−0.067	0.185	1					
Fe	0.630*	0.078	0.243	−0.380	−0.025	0.347	−0.080	0.596*	1				
Cu	0.347	0.113	0.050	0.221	−0.157	0.222	−0.414	−0.210	0.172	1			
Zn	−0.295	−0.246	−0.268	0.050	0.215	0.422	0.546	0.122	0.300	−0.302	1		
Cd	−0.776**	−0.561	0.018	0.022	−0.027	0.071	0.843**	0.310	−0.178	−0.621*	0.628*	1	
Pb	−0.193	−0.027	0.246	0.199	−0.321	−0.637*	−0.269	−0.328	−0.697*	0.116	−0.818**	−0.268	1

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

with Cd ($p < 0.05$). TOC play a vital role in Cd sorption, as the increase in organic matter will release the toxic trace elements (Rubio et al., 2000) like Cd in the sediments to bioavailable form. The significant positive correlation between cadmium and lead ($p < 0.05$) in shore sediments indicates their common source of origin from anthropogenic activities. The positive correlations of Cr and Cu with Fe and Mn suggest their association with Fe and Mn oxides (Unnikrishnan, 2000). Due to the lower capability of sandy sediments to adsorb metals (Rubio et al., 2000), grain size pattern was not much involved in making significant correlation with the trace elements in the study area.

On the basis of results by one-way ANOVA, significant differences ($p < 0.05$) were noticed in the concentrations of Zn, Cd and Pb in shore sediments. In lagoon sediments, significant differences in concentration were observed for all metals except Mn and Cu. The results are presented as mean ± SD in Table 11. The parameters with mean values that do not share the same superscript were significantly different. This could be due to the variation of receiving different amounts of trace elements that have been released from various sources (Lim et al., 2012). Principal Component Analysis (PCA) followed by Varimax with Kaiser Normalization rotation method was applied to extract variables (Fig. 5). In shore sediments, cumulative percentage and Eigen values for component1 are 36.029 and 4.684 and that of component 2 are 65.320 and 3.808. The associations of Cd and Pb with TOC and pH depict the anthropogenic input and accumulation from non-detrital sources of these elements. In lagoon sediments, cumulative percentage and eigen values for component1 are 29.294 and 3.808 and

Table 11
One-way ANOVA results of metal concentrations.

	Element	Kavaratti	Kadmat	Agatti	Homoscedasticity p-value	One-way ANOVA p-value
Shore	Cr	4.97 ± 5.84	0.35 ± 0.04	1.68 ± 0.14	0.011	0.193
	Mn	5.54 ± 4.41	1.68 ± 0.35	2.79 ± 0.13	0.013	0.143
	Fe	243.21 ± 191.69	62.98 ± 13.12	62.44 ± 7.43	0.016	0.074
	Cu	1.74 ± 1.88	2.16 ± 0.37	0.95 ± 0.79	0.073	0.383
	Zn	2.16 ± 0.37^{b}	0.18 ± 0.09^{a}	0.39 ± 0.06^{a}	0.045	**0.000**
	Cd	5.88 ± 2.62^{ab}	2.24 ± 3.39^{a}	8.22 ± 0.31^{b}	0.044	**0.023**
	Pb	37.82 ± 22.64^{a}	19.35 ± 2.84^{a}	76.84 ± 13.99^{b}	0.116	**0.002**
Lagoon	Cr	2.06 ± 0.13^{b}	1.22 ± 0.33^{a}	1.87 ± 0.30^{b}	0.094	**0.004**
	Mn	2.94 ± 0.49	2.60 ± 0.09	2.56 ± 0.38	0.193	0.313
	Fe	59.17 ± 7.36^{b}	56.28 ± 4.92^{b}	38.85 ± 5.64^{a}	0.771	**0.002**
	Cu	0.40 ± 0.14	0.97 ± 0.65	0.52 ± 0.44	0.109	0.232
	Zn	1.34 ± 0.36^{b}	0.26 ± 0.07^{a}	0.38 ± 0.23^{a}	0.151	**0.000**
	Cd	8.75 ± 0.19^{c}	4.52 ± 0.46^{a}	7.89 ± 0.47^{b}	0.11	**0.000**
	Pb	14.06 ± 9.25^{a}	64.91 ± 3.20^{b}	102.22 ± 6.03^{c}	0.255	**0.000**

Means within a row with different letters differ significantly ($p < 0.05$), evaluated either using the multiple comparison Tukey's HSD or Tamhane's T2 tests, depending on the fulfilment or not of the homoscedasticity requirement.
Homoscedasticity among processing technologies was tested by means of the Levene's test.
$p < 0.05$ indicates that the mean value of the evaluated parameter of at least one sample differs from the others (in this case multiple comparison tests were performed).

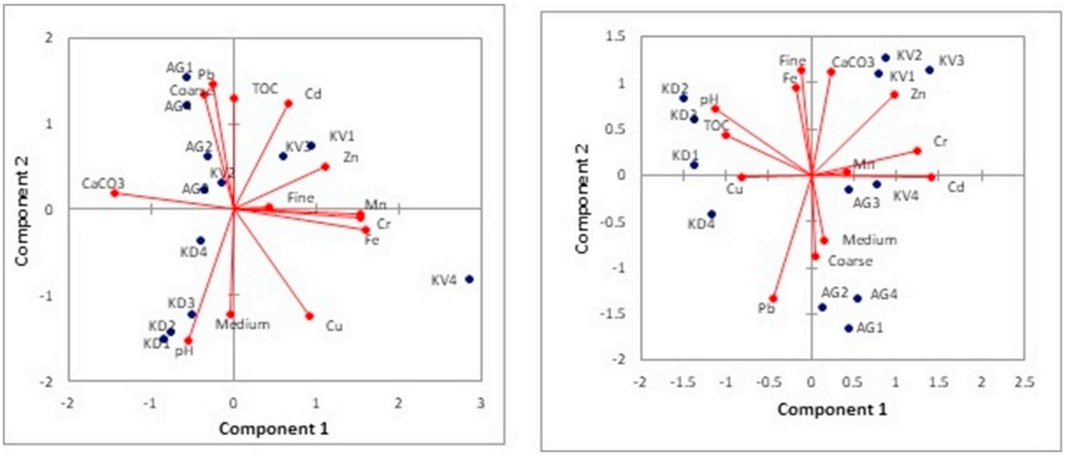

Fig. 5. PCA plot of trace elements in shore and lagoon sediments in rotated matrix.

that of component 2 are 53.888 and 3.197. Pb is not associated with any other trace elements in the matrix plot, which may be due to the anthropogenic sources of origin.

The coral reef ecosystem of Lakshadweep is facing trace metal pollution in reef sediments due to anthropogenic pressure and developmental activities. The main anthropogenic sources of trace element pollution prevailing in the islands are diesel based power generation, shipping activities, sewage sludge, plastic materials, fertilizers and construction and tourism activities. Petroleum products, paints and pigments used in plastics, garbage and phosphate fertilizers are the main sources of Cd. Changing life style coupled with population pressure has increased the dumping of untreated sewage to the shore and lagoons. Lagoons tend to concentrate these toxic wastes as they are cut off from the sea. Compared to Kadmat, the population pressure and developmental activities are more in Kavaratti and Agatti. The aircraft traffic emissions and airport associated solid wastes and chemicals are also a source of trace element pollution in Agatti. Based on the statistical reports from Lakshadweep, percentage of passenger and cargo shipping facilities, power generation, use of fertilizers and pesticides, construction and building activities, micro, small and medium scale industries has increased in the recent years. From this study, it can be generalized that Pb remains as an ecotoxicological risk for the aquatic biota, whereas Cd must be considered as a serious threat for the entire coral reef ecosystem of Lakshadweep.

Acknowledgement

The authors wish to express their gratitude to the Department of Science and Technology (DST), Govt. of India, for the financial assistance to carry out the research work.

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